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National Synchrotron Light Source

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Upton, NY 11973

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DISCLAIMER

PHOTOINJECTED ENERGY RECOVERY LINAC UPGRADE FOR THE NATIONAL SYNCHROTRON LIGHT SOURCE *

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Abstract

We describe a major paradygm shift in in the approach to the production of synchrotron radiation This change will considerably improve the scientific capabilities of synchrotron light sources. We introduce plans for an upgrade of the National Synchrotron Light Source (NSLS). This upgrade will be based on the Photoinjected Energy Recovering Linac (PERL). This machine emerges from the union of two technologies, the laser-photocathode RF gun (photoinjector) and superconducting linear accelerators with beam energy recovery (Energy Recovering Linac). The upgrade will bring the NSLS users many new insertion device beam lines, brightness greater than 3rd generation light-source's and ultra-short pulse capabilities, not possible with storage ring light sources.

1 INTRODUCTION

The science and technology of the generation of synchrotron light is facing a major paradigm shift, based on the advent of the Photoinjected Energy Recovery Linac (PERL).

Synchrotron radiation has become an integral part of the experimental portfolio in most science concerned with the structure of matter on the atomic scale. This impact is felt over a broad range of science from protein crystallography in the biological sciences to studies of atomic and electronic structure in systems ranging from high temperature superconductors to toxic elements in soil. The impact of this research has grown exponentially as the sources have evolved.

Synchrotron radiation is produced, worldwide, by about 70 storage-ring based facilities. Storage-ring based light-sources have been refined by using a high-symmetry lattice and higher energies to provide high-brightness from a large number of insertion devices. This impressive performance is nearly at its ultimate level.

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There are a few limitations. First, the emittance of a storage ring based light source is proportional to the energy (γ) squared times the angle per bend cubed, $\varepsilon \sim \gamma^2 \Delta\theta^3$. The emittance of a linac has a better scaling with energy, $\varepsilon \sim \varepsilon_n/\gamma$, where ε_n is the (invariant) normalized emittance.

With photoinjector electron sources the normalized emittance is exceptionally good, leading to a light source brightness surpassing storage rings. In addition, the linac produces naturally a round beam, with equal horizontal and vertical emittances. Another major point: Storage ring light sources produce pulses that are over 10 ps long, while linacs can achieve below 100 fs using bunch compression techniques. There are many other advantages of this approach: electro-optic control of the bunch sequence, virtual 'top-off' operation with a constant current, control of the horizontal to vertical emittance ratio and a flexible basic structure.

PERL offers crucial advantages for a new user-oriented x-ray light source, including very high brightness, a large degree of spatial coherence, and ultra-fast temporal structure. These characteristics are key to both current and future applications of synchrotron radiation probing of matter. The following provides a brief account of some of these applications.

· *Ultrafast Structural Dynamics and Processes*: The 100 fs x-ray pulses may be used for performing time domain structural dynamics measurements in condensed matter samples on the time scale of chemical bond formation and lattice vibrations. On a somewhat longer time scale, one may study temporal and spatial dependence of the response, such as magnetization and polarization, of condensed matter samples on the picosecond time scale.

· *Ultrahigh Spatial Resolution*: The brightness of the PERL is comparable or greater than that of the best 3rd generation SR sources. However, the shape of the beam can be circular in the case of PERL, an important advantage in many applications of coherent x-rays. There are two major uses of high transverse coherence sources: microscopy and coherent x-ray scattering. Both of these techniques probe matter with nanometer to Angstrom-scale spatial resolution.

· *Ultrasmall Membrane Proteins*: Because of the extraordinary brightness of PERL, it can be expected to play an important role in addressing one of the most difficult problems in protein crystallography, i.e. solving the structures of membrane proteins.

2 UNDERLYING TECHNOLOGIES

The PERL is a product of two basic, relatively new but well understood techniques: The photoinjector (short for laser photocathode RF electron gun) and the superconducting energy recovery linac. The photoinjector is the best source for the production of high-brightness electron beams. The superconducting energy recovery linac can deliver non-stored, high-current electron beams. Used in unison in the PERL these techniques promise to deliver non-stored, high-brightness, high-average-current, short-pulse electron beams.

2.1 Photoinjector Technology

The laser-photocathode RF gun (photoinjector) increased the brightness of linacs by orders of magnitude, making it possible to plan X-ray Free-Electron Lasers. Bunch compression has been developed to increase longitudinal beam brightness at the SLC at SLAC. It has been recognized that electron linacs with photoinjectors can provide GeV energy electron beams with a low emittance [1] and very short pulses [2]. That is why all currently proposed X-ray Free-Electron Laser designs are based on photoinjected linacs. The photoinjector is capable of generating a very high field on the cathode since there are no insulators to limit the electric field gradient and RF breakdown limits are many 10's of MV/m, sometimes over 120 MV/m. Thus the electron bunch is accelerated rapidly, minimizing the time spent at low velocities where space charge forces lead to emittance growth. In addition, the high field allows for a very high current emission, and the photoemission (with powerful lasers and high quantum efficiency cathodes) allow for a high current density, thus to a high beam brightness.

The PERL requires a CW operation of the photoinjector. The device that came closest to this requirement is the Boeing photoinjector [3].

The 433 MHz Boeing gun has been operated at a 25% duty factor with an average current of 135 mA during the macropulse, driven by a 13-watt laser on the photocathode. A system at a similar frequency was designed for a high power FEL [4].

The Boeing photoinjector (or one of the other alternative designs) can be improved considerably, leading to the parameters required for the PERL operation of the photoinjector gun. Producing the relatively high currents (~200 mA) anticipated for the PERL represents one of the most challenging development areas of this source. The key issue in this case is the development of a robust photocathode design and environmental structures. Thus additional R&D work must be done on the photoinjector and its laser to achieve the average current and brightness targets for the PERL. Considerable information on various options for a photoinjector for PERL can be found in a recent workshop [5]

2.2 Superconducting Energy Recovery Linac

The linac can be based on TESLA type structures or similar devices; a comprehensive summary on the performance of TESLA cavities can be found in B. Aune et al.[6].

The TESLA type cavities are very well known (from work at DESY, Stanford, industry). They are available commercially from a number of manufacturers. The shunt impedance is R/Q=1036Ω and the cavity length is 1.038m. We will specify the unloaded quality factor at $Q_0=1.5\text{x}10^{10}$ at a temperature of 2K and at a field of 20MV/m. At this level the refrigeration power is 26 W/cavity, thus for 3 GeV, 150 cavities require a refrigeration power of 4 kW.

The Energy Recovering Linac (ERL) was proposed initially for high-energy physics applications in 1965 [7]. In an energy recovering linac, a beam is accelerated to the energy required for the application (say 3 to 6-GeV for the generation of x-rays), and returned to the linac 180 degrees out of phase with respect to the accelerated electrons. In this way the returning high-energy electrons are decelerated, and they recycle their energy to the RF field to provide most of the power necessary to accelerate the entering electrons.

Thomas Jefferson National Accelerator Facility has recently demonstrated the efficacy of the principle, for an infrared FEL application, in producing a 5 mA average current in a 45 MeV linac with an essentially undetectable power loss in the linac. [8]

The use of a non-stored-beam linear accelerator for X-ray light source applications rather than a conventional storage ring was proposed several years ago by scientists in the Budker Institute of Nuclear Physics in Novosibirsk [9].

3 BEAM DYNAMICS AND OPTICS

The Photoinjected Energy Recovery Linac design study at the NSLS is considering the feasibility of a new synchrotron light source based on a 3-6 GeV energy recovering superconducting linac initiated by a photoinjected gun. To be a competitive light source the photoinjector must provide high brightness electron beams with a normalized transverse emittance of 0.5-1 mm-mrad and a bunch charge per of 0.15-0.45 nC at a rep rate of 0.43-1.3 GHz. A companion paper in this conference [10] provides an assessment of the beam dynamics issues that are critical to preserving the high brightness beams in the energy recovery linac and the return leg, including coherent synchrotron radiation effects.

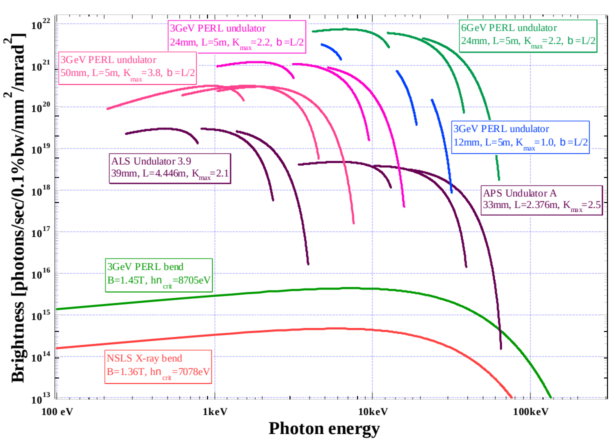
In addition to returning the electron beam to the linac with a phase shift of 180 degrees, the "return loop" of the PERL must be capable of longitudinal bunch compression, minimizing the deleterious effects of coherent synchrotron radiation [11] and provide space for up to two-dozen insertion devices. Another companion paper in this conference presents a design for the PERL optics based on tunable isochronous achromats. [12].

4 ANTICIPATED PERFORMANCE

The brightness of PERL insertion devices was calculated using the expected electron beam emittance and energy spread, and is shown in the figure below, where we compare PERL Insertion Devices and bend source brightness to ALS and APS sources as a function of photon energy on a log-log scale.

An insertion device of a 6 GeV PERL is presented by the highest brightness curve (green). Insertion Devices of a 3 GeV PERL are presented by the next three highest brightness curves (blue, violet and red). For comparison the ALS and APS sources are given in black. At the bottom, a 3 GeV PERL bend is shown in green and compared to an NSLS bend in red.

As is reported in [10-12], by a careful design of the lattice of the PERL, the emittance growth due to various single-particle and collective effects can be controlled to a very satisfactory degree even when the electron bunches are compresses to 100 fs and the emittance and energy spread growth are very minimal. Thus the PERL can deliver an ultra-high brightness with a very short pulse. It is expected that shorter



pulses will be possible, possibly with some sacrifice in brightness.

Finally, one should keep in mind that a high-brightness, multi-GeV linac is a great platform for operating Free-Electron Lasers. Calculations of high performance High-Gain Harmonic Generation FELs based on the PERL machine were made [13]. However, this is beyond the scope of this paper.

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